

## SPIN PHYSICS AT GSI\*

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Polarized antiprotons produced by spin filtering with an internal polarized gas target provide access to a wealth of single- and double-spin observables, thereby opening a window to physics uniquely accessible with the HESR at FAIR. This includes a first measurement of the transversity distribution of the valence quarks in the proton, a test of the predicted opposite sign of the Sivers-function, related to the quark distribution inside a transversely polarized nucleon, in Drell-Yan (DY) as compared to semi-inclusive DIS, and a first measurement of the moduli and the relative phase of the time-like electric and magnetic form factors  $G_{E,M}$  of the proton. In polarized and unpolarized  $p\bar{p}$  elastic scattering open questions like the contribution from the odd charge-symmetry Landshoff-mechanism at large  $|t|$  and spin-effects in the extraction of the forward scattering amplitude at low  $|t|$  can be addressed.

### 1. Physics Case

The polarized antiproton-proton interactions at the High Energy Storage Ring (HESR) at the future Facility for Antiproton and Ion Research (FAIR) will provide unique access to a number of new fundamental physics observables, which can be studied neither at other facilities nor at HESR without transverse polarization of protons and antiprotons.

#### 1.1. *The transversity distribution*

is the last leading-twist missing piece of the QCD description of the partonic structure of the nucleon. It describes the quark transverse polarization inside a transversely polarized proton <sup>2</sup>. Unlike the more conventional unpolarized quark distribution  $q(x, Q^2)$  and the helicity distribution

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\*A short version of this report can be found in ref. <sup>1</sup>.

$\Delta q(x, Q^2)$ , the transversity  $h_1^q(x, Q^2)$  can neither be accessed in inclusive deep-inelastic scattering of leptons off nucleons nor can it be reconstructed from the knowledge of  $q(x, Q^2)$  and  $\Delta q(x, Q^2)$ . It may contribute to some single-spin observables, but always coupled to other unknown functions. The transversity distribution is directly accessible uniquely via the **double transverse spin asymmetry**  $A_{TT}$  in the Drell-Yan production of lepton pairs. The theoretical expectations for  $A_{TT}$  in the Drell-Yan process with transversely polarized antiprotons interacting with a transversely polarized proton target at HESR are in the 0.3–0.4 range<sup>3,4</sup>; with the expected beam polarization achieved using a dedicated low-energy antiproton polarizer ring (AP) of  $P \approx 0.3$  and the luminosity of HESR, the PAX experiment<sup>a</sup> is uniquely suited for the definitive observation of  $h_1^q(x, Q^2)$  of the proton for the valence quarks. The determination of  $h_1^q(x, Q^2)$  will open new pathways to the QCD interpretation of single-spin asymmetry (SSA) measurements. In conjunction with the data on SSA from the HERMES collaboration<sup>5</sup>, the PAX measurements of the SSA in Drell-Yan production on polarized protons can for the first time provide a test of the theoretical prediction<sup>6</sup> of the reversal of the sign of the Sivers function<sup>7</sup> from semi-inclusive DIS to Drell-Yan production.

### 1.2. *Magnetic and electric form factors*

The origin of the unexpected  $Q^2$ -dependence of the ratio of the magnetic and electric form factors of the proton as observed at the Jefferson laboratory<sup>8</sup> can be clarified by a measurement of their relative phase in the time-like region, which discriminates strongly between the models for the form factor. This phase can be measured via SSA in the annihilation  $\bar{p}p^\uparrow \rightarrow e^+e^-$  on a transversely polarized target<sup>9,10</sup>. The first ever measurement of this phase at PAX will also contribute to the understanding of the onset of the pQCD asymptotics in the time-like region and will serve as a stringent test of dispersion theory approaches to the relationship between the space-like and time-like form factors<sup>11,12,13</sup>. The double-spin asymmetry will allow independently the  $G_E - G_M$  separation and serve as a check of the Rosenbluth separation in the time-like region which has not been carried out so far.

<sup>a</sup>PAX collaboration (**P**olarized **A**ntiproton **E**Xperiments). For the web-site, see <http://www.fz-juelich.de/ikp/pax>.

### 1.3. *Hard scattering*

Arguably, in  $p\bar{p}$  elastic scattering the hard scattering mechanism can be checked beyond  $|t| = \frac{1}{2}(s - 4m_p^2)$  accessible in the  $t$ - $u$ -symmetric  $pp$  scattering, because in the  $p\bar{p}$  case the  $u$ -channel exchange contribution can only originate from the strongly suppressed exotic dibaryon exchange. Consequently, in the  $p\bar{p}$  case the hard mechanisms<sup>14,15,16</sup> can be tested at  $t$  almost twice as large as in  $pp$  scattering. Even unpolarized large angle  $p\bar{p}$  scattering data can shed light on the origin of the intriguing oscillations around the  $s^{-10}$  behavior of the  $90^\circ$  scattering cross section in the  $pp$  channel and put stringent constraints on the much disputed odd-charge conjugation Landshoff mechanism<sup>17,18,19,20</sup>. If the Landshoff mechanism is suppressed then the double transverse asymmetry in  $p\bar{p}$  scattering is expected to be as large as the one observed in the  $pp$  case.

## 2. Towards an asymmetric polarized antiproton-proton collider at FAIR

The possibility to test the nucleon structure via double spin asymmetries in polarized proton-antiproton reactions at the HESR ring of FAIR at GSI has been suggested by the PAX collaboration in 2004<sup>21</sup>. Since then, there has been much progress, both in understanding the physics potential of such an experiment<sup>3,4,22,23</sup> and in studying the feasibility of efficiently producing polarized antiprotons<sup>24</sup>. The physics program of such a facility would extend to a new domain the exceptionally fruitful studies of the nucleon structure performed in unpolarized and polarized deep inelastic scattering (DIS), which have been at the center of high energy physics during the past four decades. As mentioned earlier, a direct measurement of the transversity distribution function  $h_1^q(x, Q^2)$ , one of the last missing fundamental pieces in the QCD description of the nucleon, is unique. In the available kinematic domain of the proposed experiment, which covers the valence region, the Drell-Yan double transverse spin asymmetry was recently predicted to be as large as 0.3<sup>3,4</sup>. Other novel tests of QCD at such a facility include the polarized elastic hard scattering of antiprotons on protons and the measurement of the phases of the time-like form factors of the proton (see Ref.<sup>21</sup>). A viable practical scheme<sup>b</sup> which allows us to

<sup>b</sup>The basic approach to polarizing and storing antiprotons at HESR-FAIR is based on solid QED calculations of the spin transfer from electrons to antiprotons<sup>25</sup>, which is being routinely used at Jefferson Laboratory for the electromagnetic form factor sep-

reach a polarization of the stored antiprotons at HESR-FAIR of  $\simeq 0.3$  has been worked out and published in Ref. <sup>24</sup>.

The PAX Letter-of-Intent was submitted on January 15, 2004. The physics program of PAX has been positively reviewed by the QCD Program Advisory Committee (PAC) on May 14–16, 2004 <sup>28</sup>. The proposal by the ASSIA collaboration <sup>29</sup> to utilize a polarized solid target and bombard it with a 45 GeV unpolarized antiproton beam extracted from the synchrotron SIS100 has been rejected by the GSI management. Such measurements would not allow one to determine  $h_1^q(x, Q^2)$ , because in single spin measurements  $h_1^q(x, Q^2)$  appears always coupled to another unknown fragmentation function. Following the QCD-PAC report and the recommendation of the Chairman of the committee on Scientific and Technological Issues (STI) <sup>28</sup> and the FAIR project coordinator, the PAX collaboration has optimized the technique to achieve a sizable antiproton polarization and the proposal for experiments at GSI with polarized antiprotons <sup>24</sup>. From various working group meetings of the PAX collaboration, presented in part in 2004 at several workshops and conferences <sup>28</sup>, we conclude:

- Polarization buildup in the HESR ring, operated at the lowest possible energy, as discussed in PAX LoI, does not allow one to achieve the optimum degree of polarization in the antiproton beam. The goal of achieving the highest possible polarization of antiprotons and optimization of the figure of merit dictates that one polarizes antiprotons in a dedicated low-energy ring. The transfer of polarized low-energy antiprotons into the HESR ring requires pre-acceleration to about 1.5 GeV/c in a dedicated booster ring. Simultaneously, the incorporation of this booster ring into the HESR complex opens up, quite naturally, the possibility of building an asymmetric antiproton-proton collider<sup>c</sup>.

The PAX collaboration proposes an approach that is composed of two phases. During these the major milestones of the project can be tested and optimized before the final goal is approached: An asymmetric proton-antiproton collider, in which polarized protons with momenta of about 3.5 GeV/c collide with polarized antiprotons with momenta up to 15 GeV/c. These circulate in the HESR, which has already been approved and will

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aration <sup>26</sup>, and which has been tested and confirmed experimentally in the FILTEX experiment <sup>27</sup>.

<sup>c</sup>It should be noted that within the PAX collaboration we realized the possibility of building an asymmetric collider only later, i.e. after the oral presentation at SPIN2004.

serve the PANDA experiment. In the following, we will briefly describe the overall machine setup of the HESR complex, schematically depicted in Fig. 1.

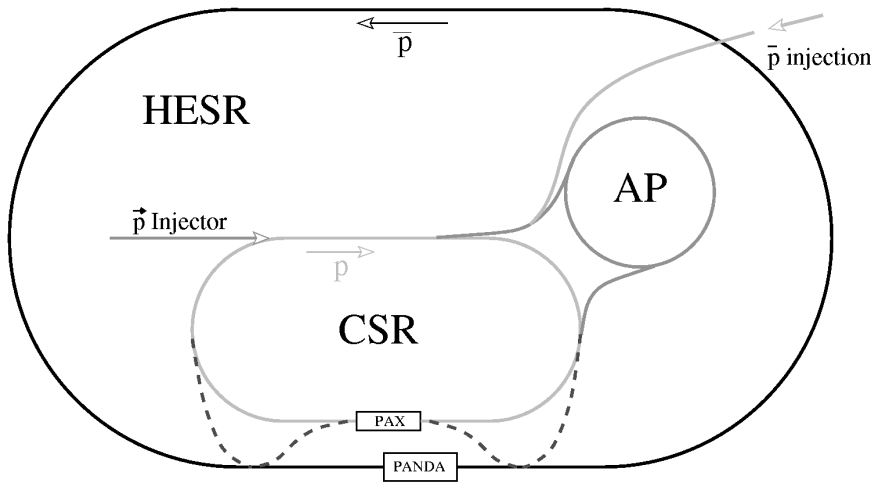


Figure 1. The proposed accelerator set-up at the HESR (black), with the equipment used by the PAX collaboration in Phase I: CSR (light gray), AP, beam transfer lines and polarized proton injector (dark gray). In Phase II, by adding two transfer lines (dashed), an asymmetric collider is set up. It should be noted that, in this phase, also fixed target operation at PAX is possible.

Let us summarize the main features of the accelerator setup:

1. An Antiproton Polarizer (AP) built inside the HESR area with the crucial goal of polarizing antiprotons at kinetic energies around  $\approx 50$  MeV ( $p \approx 300$  MeV/c), to be accelerated and injected into the other rings.
2. A second Cooler Synchrotron Ring (CSR, COSY-like) in which protons or antiprotons can be stored with a momentum up to 3.5 GeV/c. This ring shall have a straight section, where a PAX detector could be installed, running parallel to the experimental straight section of HESR.
3. By deflection of the HESR beam into the straight section of the CSR, both the collider or the fixed-target mode become feasible.

It is worthwhile to stress that, through the employment of the CSR, effectively a second interaction point is formed with minimum interference with

PANDA. The proposed solution opens the possibility to run two different experiments at the same time.

In the following sections, we discuss the physics program, which should be pursued in two different phases.

### 2.1. Phase I

A beam of unpolarized or polarized antiprotons with momentum up to 3.5 GeV/c in the CSR ring, colliding on a polarized hydrogen target in the PAX detector. This phase is independent of the HESR performance.

This first phase, at moderately high energy, will allow for the first time the measurement of the time-like proton form factors in single and double polarized  $\bar{p}p$  interactions in a wide kinematical range, from close to threshold up to  $Q^2 = 8.5 \text{ GeV}^2$ . It would enable to determine several double spin asymmetries in elastic  $\bar{p}^\uparrow p^\uparrow$  scattering. By detecting back scattered antiprotons one can also explore hard scattering regions of large  $t$ : In proton-proton scattering the same region of  $t$  requires twice the energy. There are no competing facilities at which these topical issues can be addressed. For the theoretical background, see the PAX LoI<sup>21</sup> and the recent review paper<sup>10</sup>.

### 2.2. Phase II

This phase will allow the first ever direct measurement of the quark transversity distribution  $h_1$ , by measuring the double transverse spin asymmetry  $A_{TT}$  in Drell-Yan processes  $p^\uparrow \bar{p}^\uparrow \rightarrow e^+ e^- X$  as a function of Bjorken  $x$  and  $Q^2 (= M^2)$

$$A_{TT} \equiv \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}} = \hat{a}_{TT} \frac{\sum_q e_q^2 h_1^q(x_1, M^2) h_1^{\bar{q}}(x_2, M^2)}{\sum_q e_q^2 q(x_1, M^2) \bar{q}(x_2, M^2)},$$

where  $q = u, \bar{u}, d, \bar{d} \dots$ ,  $M$  is the invariant mass of the lepton pair and  $\hat{a}_{TT}$ , of the order of one, is the calculable double-spin asymmetry of the QED elementary process  $q\bar{q} \rightarrow e^+ e^-$ . Two possible scenarios might be foreseen to perform the measurement, which are discussed below.

#### 2.2.1. Asymmetric collider

A beam of polarized antiprotons from 1.5 GeV/c up to 15 GeV/c circulating in the HESR, colliding on a beam of polarized protons with momenta up

to 3.5 GeV/c circulating in the CSR. This scenario however requires to demonstrate that a suitable luminosity is reachable. Deflection of the HESR beam to the PAX detector in the CSR is necessary (see Fig. 1).

By proper variation of the energy of the two colliding beams, this setup would allow a measurement of the transversity distribution  $h_1$  in the valence region of  $x > 0.05$ , with corresponding  $Q^2 = 4 \dots 100 \text{ GeV}^2$  (see Fig. 2).  $A_{TT}$  is predicted to be larger than 0.3 over the full kinematic range, up to the highest reachable center-of-mass energy of  $\sqrt{s} \sim \sqrt{200}$ . The cross section is large as well: With a luminosity of  $5 \cdot 10^{30} \text{ cm}^{-2}\text{s}^{-1}$  about 2000 events per day can be expected<sup>d</sup>. For the transversity distribution  $h_1$ , such an experiment can be considered as the analogue of polarized DIS for the determination of the helicity structure function  $g_1$ , i.e. of the helicity distribution  $\Delta q(x, Q^2)$ ; the kinematical coverage  $(x, Q^2)$  will be similar to that of the HERMES experiment.

### 2.2.2. High luminosity fixed target experiment

If the required luminosity in the collider mode is not achievable, a fixed target experiment can be conducted. A beam of 22 GeV/c (15 GeV/c) polarized antiprotons circulating in the HESR is used to collide with a polarized internal hydrogen target. Also this scenario requires the deflection of the HESR beam to the PAX detector in the CSR (see Fig. 1).

A theoretical discussion of the significance of the measurement of  $A_{TT}$  for a 22 GeV/c (15 GeV/c) beam impinging on a fixed target is given in Refs. <sup>3,4,23</sup> and the recent review paper <sup>10</sup>. The theoretical work on the  $K$ -factors for the transversity determination is in progress <sup>30,31</sup>. This measurement will explore the valence region of  $x > 0.2$ , with corresponding  $Q^2 = 4 \dots 16 \text{ GeV}^2$  (see Fig. 2). In this region  $A_{TT}$  is predicted to be large (of the order of 0.3, or more) and the expected number of events can be of the order of 2000 per day.

We would like to mention, that we are also investigating whether the PANDA detector, properly modified, is compatible with the transversity measurements in the collider mode, where an efficient identification of the Drell-Yan pairs is required. At the interaction point, the spins of the colliding protons and antiprotons should be vertical, with no significant component along the beam direction.

<sup>d</sup>A first estimate indicates that in the collider mode luminosities in excess of  $10^{30} \text{ cm}^{-2}\text{s}^{-1}$  could be reached. We are presently evaluating the influence of intra-beam scattering, which seems to be one of the limiting factors.

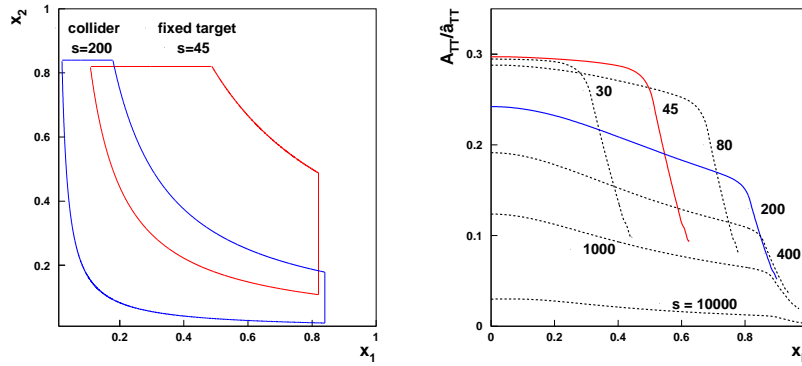


Figure 2. Left: The kinematic region covered by the  $h_1$  measurement at PAX in phase II. In the asymmetric collider scenario antiprotons of 15 GeV/c impinge on protons of 3.5 GeV/c at c.m. energies of  $\sqrt{s} \sim \sqrt{200}$  GeV and  $Q^2 > 4$  GeV<sup>2</sup>. The fixed target case represents antiprotons of 22 GeV/c colliding with a fixed polarized target ( $\sqrt{s} \sim \sqrt{45}$  GeV). Right: The expected asymmetry as a function of Feynman  $x_F$  for different values of  $s$  and  $Q^2 = 16$  GeV<sup>2</sup>.

### 3. Conclusion

To summarize, we note that the storage of polarized antiprotons at HESR will open unique possibilities to test QCD in hitherto unexplored domains. This will provide another cornerstone to the antiproton program at FAIR.

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